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Early Paleocene Magnetostratigraphy and Revised Biostratigraphy of the Ojo Alamo Sandstone and Lower Nacimiento Formation, San Juan Basin, New Mexico, USA

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ABSTRACT

The lower Paleocene Ojo Alamo Sandstone and Nacimiento Formation from the San Juan Basin (SJB) in northwestern New Mexico preserve arguably the best early Paleocene mammalian record in North America and is the type location for the Puercan (Pu) and Torrejonian (To) North American Land Mammal ages (NALMA). However, the lack of precise depositional age constraints for the Ojo Alamo Sandstone and lower Nacimiento Formation has hindered our understanding of the timing and pacing of mammalian community change in the SJB following the Cretaceous-Paleogene mass extinction. Here we produced a high-resolution age model for the Ojo Alamo Sandstone and lower Nacimiento formation combining magnetostratigraphy and $^{40}Ar/^{39}Ar$ geochronology spanning the first ~3.5 Myr of the Paleocene. Mean sediment accumulation rates during C29n were relatively low (<50 m/Myr) and equalized from basin center to basin margin indicating an accommodation minimum; sediment accumulation rates roughly double (> 90m/Myr) during C28r and are highest in the basin center and lowest on basin margin indicating high accommodation and an increase in basin subsidence near the C29n/C28r boundary (~64.96 Ma). Puercan fossil localities were restricted to C29n, Torrejonian 1 localities to C28n, and lower Torrejonian 2 localities to C27r. Our revised age model for the SJB suggests that the first appearance of To1 mammals may have been diachronous across North America, with the Torrejonian 1 mammals first appearing in the north (Montana and North Dakota) during C29n, then in middle latitudes (Utah) in C28r, and lastly in southern North America (New Mexico) in C28n.

INTRODUCTION

The Ojo Alamo Sandstone and the Nacimiento Formation from the San Juan Basin (SJB) in northwestern New Mexico and southwestern Colorado (fig. 1) preserve a nearly continuous succession of lower Paleocene terrestrial deposits (e.g., Baltz et al., 1966; O'Sullivan et al., 1972; Williamson, 1996; Williamson et al., 2008; Cather et al., 2019). The SJB also preserves one of the most complete records of early Paleocene mammalian evolution following the Cretaceous-Paleogene (K-Pg) mass extinction and has been extensively studied for over a century (e.g., Granger, 1917; Matthew, 1937; Simpson, 1959; Williamson and Lucas, 1992; Williamson, 1996; Williamson et al., 2015). The early Paleocene Puercan and Torrejonian North American Land Mammal ages (NALMAs) were defined using SJB fossil mammalian faunas (Wood et al., 1941). These land mammal ages were subsequently divided into biochrons, based largely on the SJB record, and are used for early Paleocene correlation across North America (Lindsay, 2003; Lofgren et al., 2004).

Two intervals of potentially rapid mammalian turnover, between Puercan 2 (Pu2) and Puercan 3 (Pu3), and between Torrejonian 2 (To2) and Torrejonian 3 (To3) faunas, were documented by Williamson (1996). Additionally, the boundary between Pu3 and Torrejonian 1 (To1) records the near total replacement of mammalian communities with new species and potentially represents another time period of high mammalian turnover (Williamson, 1996). While Leslie et al. (2018b) were able to develop a high resolution age model for the To2-To3 transition, no high resolution age models exist for the Pu2-Pu3 and Pu3-To1 transitions in the SJB, limiting our understanding of the timing and rate of faunal change through this crucial time interval.

Previous work has used magnetostratigraphy to develop an age model for the Ojo Alamo Sandstone and lower Nacimiento Formation with the goal of identifying the K-Pg boundary and evaluating the chronology of mammalian evolution within the SJB (e.g., Butler et al., 1977; Butler and Taylor, 1978; Lindsay et al., 1978, 1981; Taylor and Butler, 1980; Butler and Lindsay, 1985; Fassett, 2009). However, sample spacing was at relatively large and mammal localities were not always precisely correlated to within the magnetostratigraphic sections, which has meant that there is not a high-resolution age model for Ojo Alamo Sandstone or lower Nacimiento Formation. Additionally, the age and duration of type section of the Nacimiento Formation at Mesa de Cuba (Cope, 1875) has never been determined.

The lack of detailed geochronology for the Ojo Alamo Sandstone and confusion about its stratigraphic terminology has meant that the age determinations for this unit have been contentious (see discussions in, Williamson and Weil, 2008a, 2008b). The lack of an age model for the Ojo Alamo Sandstone and confusion about stratigraphic terminology has also lead some previous authors to suggest the existence of early Paleocene dinosaurs from the San Juan Basin (e.g., Fassett et al., 2002, 2011; Fassett, 2009). However, these interpretations were made based on an incorrect interpretation of previously published magnetostratigraphy and the purported presence of Paleocene pollen, which has not been replicated, casting doubts upon their validity (e.g., Lucas et al., 2009)

In this study, we developed a high-resolution magnetostratigraphic age model for the Ojo Alamo Sandstone and lower Nacimiento Formation spanning the Puercan and early Torrejonian (To1-To2) interval from seven measured sections encompassing the first ~3.5 Myr of the Paleocene. These sections, from northwest to southeast, are (1) Kutz Canyon, (2) Gallegos Canyon, (3) Chico Springs, (4) De-Na-Zin, (5) Kimbeto Wash, (6) Betonnie Tsosie Wash, and

(7) Mesa de Cuba (fig. 1). Local polarity zones from each section, constrained by $^{40}Ar/^{39}Ar$ ash and detrital sanidine ages, were correlated to the global geomagnetic polarity time scale (GPTS) (Ogg, 2012). Sediment accumulation rates were calculated for each section and/or magnetic chrons within the sections and used to develop an age model for the Ojo Alamo Sandstone and the base of the Nacimiento Formation. This age model presented was then correlated with the magnetostratigraphic sections of Leslie and others (2018b) to develop a basin-wide age model for the entire lower Paleocene in the SJB. This age model was then used to assess the basin evolution of the SJB during the early Paleocene. The age model was then used to constrain the age of Puercan and early Torrejonian (To1 – To2) fossil localities across the SJB. These revised ages for the Puercan and Torrejonian mammal sites have important implications for understanding the tempo of mammalian turnover after the end-Cretaceous mass extinction and the timing of key events in early mammal evolution.

PREVIOUS STUDIES

Geologic Background

The SJB is a Laramide foreland basin in northwest New Mexico and southwest Colorado that preserves a nearly continuous succession of Upper Cretaceous (Campanian) to lower Eocene terrestrial deposits (Baltz et al., 1966; Chapin and Cather, 1983). Cather (2004) argued for three distinct subsidence phases in the SJB: (1) an early phase during the late Campanian – early Maastrichtian, (2) a middle phase during the late Maastrichtian – early Paleocene, and (3) a late phase during the Eocene. The middle phase of subsidence was hypothesized to allow for deposition of lower Paleocene sediments in the basin (Cather, 2004).

The SJB preserves two lower Paleocene formations: (1) the Ojo Alamo Sandstone and (2) the Nacimiento Formation (Baltz et al., 1966; O'Sullivan et al., 1972). The Ojo Alamo Sandstone unconformably overlies the Maastrichtian Naashoibito Member of the Kirtland Formation and is composed of gold to yellow colored, cross-bedded, medium to coarse-grained sandstone with interbedded sandstone and siltstone deposits, and localized carbonaceous shale beds. These deposits have been interpreted to represent an alluvial plain in a seasonally dry, sub-tropical climate with one or more sediment sources in the southern Rocky Mountains (Flynn and Peppe, in press; Baltz et al., 1966; O'Sullivan et al., 1972; Powell, 1973; Tidwell et al., 1981; Chapin and Cather, 1983; Sikkink, 1987; Cather, 2004). Herein we recognize the Ojo Alamo Sandstone as a separate stratigraphic formation of Baltz et al. (1966). For clarity, the Ojo Alamo Sandstone is equivalent to the Kimbeto Member of the Ojo Alamo Formation proposed by Sullivan et al. (2005).

The Nacimiento Formation conformably overlies the Ojo Alamo Sandstone and unconformably underlies the Eocene San Jose Formation. The Nacimiento Formation is subdivided into six members: (1) The Kutz , (2) Tsosie, (3) Angel Peak, (4) Arroyo Chijuillita, (5) Ojo Encino, and (6) Escavada Members (Williamson and Lucas, 1992; Williamson, 1996; Cather et al., 2019). This study focuses on the Kutz, Tsosie, Arroyo Chijuillita and Ojo Encino Members. The Arroyo Chijuillita and Ojo Encino Members are confined to the southern portion of the basin. The Arroyo Chijuillita Member is composed of drab mudstones and small lenticular sandstone beds (Davis et al., 2016). The Ojo Encino Member contains variegated red and drab mudstones, large sheet and channel sandstone units, and three persistent intervals consisting of numerous "black" paleosol horizons referred to as the "lower", "middle", and "upper black mudstone" (Leslie et al., 2018b). Both members have been interpreted to represent meandering fluvial systems deposited in a subtropical climate, with an increase in depositional energy from the Arroyo Chijuillita to Ojo Encino Member (Flynn and Peppe, in press; Tidwell et al., 1981; Williamson, 1996; Davis et al., 2016). The Kutz Member is equivalent to the “main body” of Williamson (1996) and is primarily exposed in Kutz Canyon. It is a thick succession of cross-bedded channel sandstones, splay sandstones, and floodplain mudstones. The lower Kutz Member tends to be drab in color and becomes more variegated with reddish mudstones in the upper portion (Cather et al., 2019). The Tsosie Member is exposed in the southwestern part of the basin and is characterized by thick, cross-bedded channel sandstone complexes separated by mostly drab floodplain mudstones. The channel sandstones were interpreted as deposits from a river with a maximum depth of at least 5 m (Cather et al., 2019).

Mammalian Biostratigraphy

Puercan Mammalian Biostratigraphy

The first mammalian biostratigraphy for the lower Nacimiento Formation was proposed by Sinclair and Granger (1914), who identified two zones - the lower *Ectoconus* zone and the upper *Taeniolabis* zone – in exposures from De-Na-Zin, Kimbeto, and Betonnie Tsosie washes. They distinguished the two zones by the presence of the large-bodied multituberculate *Taeniolabis* in the upper horizon, but noted that *Ectoconus* was known from both horizons (Sinclair and Granger, 1914). Wood et al. (1941) later placed both the *Ecotconus* and *Taeniolabis* zones from Sinclair and Granger (1914) in the Puercan NALMA and designated the Nacimiento Formation fauna as representative of the Puercan. The significance of the *Ectoconus* and *Taeniolabis* zones as defined by Sinclair and Granger (1914) was debated due to both zones being present superpositionally only in De-Na-Zin and because the difference between the two zones may reflect differences in facies and/or collection intensity (Lindsay et al., 1981; Archibald et al., 1987; Williamson, 1996).

Archibald et al. (1987) redefined the early Paleocene NALMAs and subdivided the Puercan into three biochronologic zones (see Lindsay, 2003) defined by the succession of unrelated taxa. In this revision, only the younger two zones, Pu2 and Pu3, are recognized in the SJB, and the earliest zone (Pu1) is absent. The *Ecotconus* and *Taeniolabis* biostratigraphic zones of Sinclair and Granger (1914) approximately correlate temporally with the Pu2 and Pu3 biochrons of Archibald et al. (1987). Archibald et al. (1987) equated the Pu2 interval with the *Ectoconus-Taeniolabis taoensis* zone and the Pu3 interval with the *Taeniolabis taoensis-Periptychus* zone in the SJB. Williamson (1996) later revised the SJB biostratigraphy based on taxon ranges not included in Archibald et al. (1987) and approximately equated their Pu2 interval to the *Hemithlaeus kowalevskianus-Taeniolabis taoensis* zone (H-T Zone) and the Pu3 interval to the *Taeniolabis taoensis-Periptychus carinidens* zone (T-P Zone). We here refer to these last two biostratigraphic zones as Pc1 and Pc2, respectively, to distinguish them from the biochronological Puercan Pu2 and Pu3 subzones. The revision of early Paleocene NALMAs by Lofgren et al. (2004) used the same biozones defined by Archibald et al. (1987). Multiple authors (e.g., Archibald et al., 1987; Williamson and Lucas, 1992; Williamson, 1996) have noted that the fossil horizons in the SJB that yield both Pu2 and Pu3 mammalian faunas occur in C29n, which has made precise age control difficult and has inhibited temporal correlation both within the basin and across North America for each NALMA interval.

Williamson (1996) observed a potential decrease in species and generic diversity between the Pu2 and Pu3 mammalian faunas. Several mammalian taxa which are abundant in Pu2 faunas, mostly periptychid “condylarths”, are absent from the succeeding Pu3 faunal interval (Williamson, 1996). Williamson (1996) also noted a relatively high rate of origination in the Pu3 interval, but attributed this observation to immigration of taxa from northern North America. However, previous relatively low precision temporal constraints on this turnover have obscured the timing and rate of mammalian faunal changes.

Torrejonian Mammalian Biostratigraphy

Sinclair and Granger (1914) recognized two biostratigraphic faunal zones – a lower *Deltatherium* and an upper *Pantolambda* zone – stratigraphically above the Puercan faunas from Torreon Wash. Osborn (1929) treated the *Deltatherium* and *Pantolambda* zones as temporally distinct “life zones.” Wood et al. (1941) placed the *Deltatherium* and *Pantolambda* zones within the Torrejonian NALMA, which was separated from the Puercan NALMA by the Dragonian NALMA. Tomida (1981) proposed a further subdivision of the Torrejonian NALMA with the retention of the previous *Deltatherium* and *Pantolambda* zones and the addition of an older *Periptychus-Loxolophus* zone. Additionally, because the “Dragonian” NALMA was shown to overlap with their *Periptychus-Loxolophus* zone (Tomida and Butler, 1980; Tomida, 1981; Archibald et al., 1987) and Archibald et al. (1987) considered the “Dragonian” to be part of the Torrejonian NALMA.

Archibald et al. (1987) proposed three Torrejonian biochronologic interval zones in their revision of the early Paleocene: the *Periptychus carinidens-Tetraclaenodon* interval zone (To1), *Tetraclaenodon-Pantolambda* interval zone (To2), and *Pantolambda-Plesiadapis praecursor* interval zone (To3). The To1 zone was equivalent to the *Periptychus-Loxolophus* zone and the “Dragonian” interval (Wood et al., 1941; Tomida, 1981), and the To2 and To3 interval zones were approximately equivalent to the previous *Deltatherium* and *Pantolambda* zones (Osborn, 1929; Tomida, 1981). Williamson (1996) redefined and further subdivided the Torrejonian interval zones into six local biostratigraphic zones in the SJB based on new fossil discoveries — (1) *Periptychus carinidens-Protoselene opisthacus* Zone (P-P Zone; referred to here as Tj1), (2) *Protoselene opisthacus-Ellipsodon grangeri* Zone (P-E Zone; referred to here as Tj2), (3) *Ellipsodon grangeri-Arctocyon ferox* Zone (E-A Zone; referred to here as Tj3), (4) *Arctocyon ferox-Pantolamda cavirictum* Zone (A-P Zone; referred to here as Tj4), (5) *Pantolamda cavirictum-Mixodectes pugens* Zone (P-M Zone; referred to here as Tj5), and (6) *Mixodectes pugens* Zone (M Zone; referred to here as Tj6). This new zonation showed some temporal overlap in the mammalian taxa used to define the Torrejonian interval zones by Archibald et al. (1987). Subsequently, high-resolution stratigraphic correlation of the upper Nacimiento Formation, discovery of new mammalian taxa, and stratigraphic range extensions for some mammalian taxa has led to the revisions of some of these biozone (Leslie et al., 2018b).

In their update of early Paleocene NALMAs, Lofgren et al. (2004) redefined the To1 biochronologic interval zone as the *Periptychus carinidens-Protoselene opisthacus* zone (approximately equivalent to the P-P [Tj1] zone from Williamson, 1996), the To2 interval zone as the *Protoselene opisthacus-Mixodectes pugens* Zone (approximately equivalent to the P-E [Tj2], E-A [Tj3], A-P [Tj4], and P-M [Tj5] zones from Williamson, 1996), and To3 interval zone as the *Mixodectes pugens-Plesiadapis praecursor* Zone (approximately equivalent to the M [Tj6] Zone from Williamson, 1996).

In the SJB, the Tj1 zone (approximately temporally equivalent to To1) is poorly fossiliferous (Williamson, 1996), with fossil mammal collections existing from Kutz Canyon, De-Na-Zin, Kimbeto Wash, Betonnie Tsosie Wash, and Mesa de Cuba. Biozones Tj2 – Tj5 (approximately temporally equivalent to To2) are significantly more fossiliferous and collections have been made primarily from Kutz Canyon, Gallegos Canyon, Kimbeto Wash, Escavada Wash, and Torreon Wash (Williamson, 1996; Leslie et al., 2018b). The Tj6 zone (approximately temporally equivalent to To3) is also relatively well collected, with samples primarily from Escavada, Alemita Arroyo, Torreon Wash, and San Isidro Arroyo (Williamson, 1996; Leslie et al., 2018b). Previous magnetostratigraphy in the SJB has constrained Tj1 fossil localities to within C28n, Tj2-Tj5 fossil localities to within C27r, and Tj6 fossil localities to within C27n (Lindsay et al., 1978; Butler and Lindsay, 1985; Williamson and Lucas, 1992; Leslie et al., 2018b).

Magnetostratigraphy and Rock Magnetism

There is a long history of magnetostratigraphy and rock magnetism research focused on the Ojo Alamo and Nacimiento Formations in the SJB. In the original magnetostratigraphic studies of the Ojo Alamo Sandstone and Nacimiento Formation from measured sections in De-Na-Zin, Kimbeto Wash, Betonnie Tsosie Wash (also referred to as Tsosie Wash), and Kutz Canyon, the local polarity stratigraphy was incorrectly correlated to the GPTS (Butler et al., 1977; Lindsay et al., 1978, 1981). In this work, the K-Pg boundary was interpreted to be in C29n, the Ojo Alamo Sandstone was correlated with C28r, Puercan mammalian localities (*Ectoconus* and *Taeniolabis* Zones) with C28n, and the Torrejonian aged strata were correlated with C27n to C26n (Butler et al., 1977; Lindsay et al., 1978, 1981; Taylor and Butler, 1980). Butler and Lindsay (1985) later documented previously unrecognized magnetic overprinting in the Lower Cretaceous and lower Paleocene samples and revised these magnetostratigraphic interpretations for the SJB, placing the K-Pg boundary and deposition of the Ojo Alamos Sandstone in C29r, the Puercan zone mammalian localities in C29n, and the Torrejonian mammalian localities from Kutz Canyon in C28n-26n. However, the sample spacing of these studies was relatively coarse, making it difficult to precisely determine the stratigraphic position of chron boundaries or to calculate reasonable sediment accumulation rates. Thus, it has not been possible to estimate the age of the fossil localities in the SJB more precisely than an estimated position within a chron. Further, although Mesa de Cuba is the type section for the Nacimiento Formation (Cope, 1875), no previous magnetic polarity stratigraphy has been constructed there.

Butler and Lindsay (1985) analyzed the rock magnetics of SJB samples from nine stratigraphic levels from the Upper Cretaceous through middle Paleocene. The results from Butler and Lindsay (1985) indicated that titanohematite of intermediate composition was the dominant magnetic mineral in the Nacimiento Formation. They suggested that the most likely source for this was the Cretaceous volcanics of the San Juan Mountains to the north that were eroded during the Paleocene. The anisotropy of remanence of Nacimiento Formation samples from Kutz Canyon measured by Kodama (1997) supported primary detrital magnetization for the Nacimiento Formation. Leslie et al. (2018b) found the upper Nacimiento Formation had a mixed magnetic mineralogy with titanohematite and maghemite as the characteristic remanent magnetization carriers. Geothite was also present in all upper Nacimiento lithologies and dominated low-temperature magnetic measurements, but was not found to contribute to the characteristic remanence measurements (Leslie et al., 2018b).

METHODS

Lithostratigraphy

Seven lithologic and magnetostratigraphic sections were measured across ~110 km northwest to southeast transect: (1) a 129 m section from Kutz Canyon, (2) a 68 m section at Gallegos Canyon, (3) a 58 m section at Chico Springs, (4) a 125 m section from De-Na-Zin, (5) an 82.1 m section from Kimbeto Wash, (6) a 115 m section from Betonnie Tsosie Wash, and (7) a 156 m section from Mesa de Cuba (figs. 1-3). At Gallegos Canyon, De-Na-Zin, Betonnie Tsosie Wash, and Mesa de Cuba, the base of the sections were measured from the lithologic contact between the Ojo Alamo Sandstone and Nacimiento Formation (figs. 2 and 3). The section at Kimbeto Wash began above the Ojo Alamo Sandstone-Nacimiento Formation contact and was ~8 m below vertebrate horizon 2 (table 1, fig. 3) (Williamson, 1996). The Kutz Canyon section began ~4 m below vertebrate horizon 11 (Williamson, 1996) to ensure overlap with correlative biozones. The top of the Kutz Canyon section was measured to the vertebrate locality "Bab's Basin", which is at the base of the Kutz Canyon measured section of Leslie et al. (2018b). The Chico Springs lithostratigraphic and magnetostratigraphic section began approximately 8 m below fossil horizon 13 (table 1, fig. 4). Williamson (1996) produced relatively detailed measured sections through Kutz Canyon, De-Na-Zin, Kimbeto Wash, and Betonnie Tsosie Wash. Where possible, those sections were correlated to the measured sections presented here.

Each measured section was trenched to remove weathered material and to allow recording of lithologic contacts. The stratigraphic sections were measured at ~0.5 – 1.0 m resolution and the lithology and sedimentary structures of each sampling horizon were documented. Additionally, the nature of lithologic contacts was documented. For relatively thick (> 3 m) heterolithic units, the major rock types were recorded. For sandstones, the grain size(s) and relationship to surrounding strata were recorded. Potential unconformities were recognized by erosive contact and abrupt increases in grain size between adjacent strata.

The stratigraphic position of most vertebrate fossil intervals (table 1, Table DR4) within each measured section was documented in the field; for those whose stratigraphic position was not measured for this study, their stratigraphic position relative to major lithologic contacts from

Williamson (1996) was used and correlated with our measured sections (figs. 2-4). Table 1 documents the 14 vertebrate fossil-bearing intervals, the generalized area, the associated biochronologic interval zone (Lofgren et al., 2004), San Juan Basin biostratigraphic zone (Williamson, 1996), and the age of the vertebrate horizon calculated in this study using sediment accumulation rates. For vertebrate horizons 15-23, their generalized area, the associated biochronologic interval zone (Lofgren et al., 2004), San Juan Basin biozone (Williamson, 1996), and the calculated age of the vertebrate horizon are from Leslie et al. (2018b). The stratigraphic position of and locality number(s) within each vertebrate horizon is included in Table DR4.

Magnetostratigraphy and Magnetic Mineralogy

Four paleomagnetic samples were collected from a single stratigraphic horizon from mudstones, shales, paleosols, and fine-grained sandstones at ~1.5 to 3 m intervals (0.20 m minimum, 20.75 m maximum) in each measured section. Lithologies coarser than fine-grained sandstones were avoided if possible and site spacing was primarily dictated by both lithology and rock exposure. To generate paleomagnetic samples, a flat face was created *in situ* on unweathered rock surfaces using a hand rasp and the orientation of the created surface was measured using a Brunton Pocket Transit Compass. The samples were then cut into approximately 2-4 cm^3 cubes using a diamond-bit saw at Baylor University with each sample producing one cube.

Samples were collected from Gallegos Canyon, De-Na-Zin, Kimbeto Wash, and Betonnie Tsosie Wash across the entire Puercan interval; additionally, samples were collected from De-Na-Zin, Kimbeto Wash, and Betonnie Tsosie Wash from Tj1 strata (figs. 2 and 3) (Williamson, 1996). Samples were collected from Kutz Canyon spanning upper Tj1 toTj3 strata (fig. 4) (Williamson, 1996). Samples were collected from Chico Springs spanning lower Tj2 strata (fig. 4) (Williamson and Lucas, 1997). While the Mesa de Cuba section is poorly fossiliferous, and the position of the fossil localities relative to the biostratigraphic and biochronologic intervals is unclear, samples were collected from strata presumed to represent late Pc2 to Tj3 zones (fig. 4) (Williamson, 1996).

Specimens were measured at Baylor University using a 2G Enterprises (Mountain View, California) cryogenic DC-SQuID magnetometer located in a 2-layer magneto-static shielded room with a background field typically less than 300 nT. Thermal demagnetization steps were performed in 25-50 °C increments to a maximum unblocking temperature or until magnetization became erratic and unreliable, typically ranging between 250-580 °C. To minimize oxidation reactions, thermal demagnetization was conducted in a nitrogen atmosphere using an ASC (Carlsbad, California) controlled atmosphere thermal demagnetizer.

Principal component analysis (PCA) was used to determine the characteristic remanent magnetism for each demagnetized sample at each thermal demagnetization step (Kirschvink, 1980). A best fit line was calculated for samples with at least 3 stable demagnetization steps that trended towards the origin and a had maximum angle of deviation (MAD) < 20° (figs. 5A-E and 6A; Table DR1). Great circles were calculated for samples that did not have at least 3 stable demagnetization steps trending towards the origin, but did trend towards the origin before complete demagnetization; only great circles with a MAD < 20° were used (Table DR3). Virtual geomagnetic pole directions for great circles were calculated using the last stable end point from the great circle calculation. Samples with erratic demagnetizations trajectories were excluded from all further analyses (fig. 5F). Site mean directions were calculated from sampling horizons with three significant sample directions using Fisher Statistics (Fig. 5A; Table DR2) (Fisher, 1953). Site means with a 95% confidence circle $\alpha_{95} > 35°$ were not used (Watson, 1956). When no depositional unconformity was interpreted, reversal boundaries were placed at the stratigraphic midpoint between samples with opposite polarity. In instances where an unconformity was interpreted, reversal boundaries were placed at the lithologic contact equivalent with the unconformity. The local polarity stratigraphy for each section was correlated with the geomagnetic polarity timescale (GTPS) (Ogg, 2012).

To determine the primary and secondary magnetic carriers in mixed mineralogy samples, a triaxial isothermal remanent magnetization (IRM) Lowrie test (Lowrie, 1990) was performed on 10 samples that represented the range of lithologies that occur within the Ojo Alamo Sandstone and lower Nacimiento Formation at Baylor University. A 1T, 300 mT, and 100 mT field was imparted along the X, Y, and Z axes, respectively, using an ASC pulse magnetizer. Samples were then thermally demagnetized in 25 °C increments from 100 to 200 °C and 50 °C increments from 200 to 700 °C using an ASC controlled atmosphere thermal demagnetizer in an N_2 atmosphere. The magnetization in the X, Y, and Z axes was measured at each temperature step using the 2G cryogenic DC-SQuID magnetometer.

Sediment accumulation rates were calculated for each complete chron (i.e., both the lower and upper reversal was present) in each measured section and then used the sediment accumulation rates to estimate total section duration and age of mammal fossil horizons (Tables 1, 3-5). We used the duration and uncertainty of each magnetic chron Ogg (2012) and the stratigraphic thickness and associated measurement uncertainties (table 3) to calculate sediment accumulation rates. The rates are asymmetrical due to different stratal thicknesses and chron durations used in their calculations. The maximum sediment accumulation rate was calculated by dividing the maximum thickness and the minimum duration of the magnetic chron while the minimum sediment accumulation rates was calculated using the minimum thickness and the maximum duration of the magnetic chron (table 4). We were able to calculate reliable sediment accumulation rates for C29n from De-Na-Zin and Betonnie Tsosie Wash, for C28r from De-Na-Zin, Kimbeto Wash, Betonnie Tsosie Wash, and Mesa de Cuba, and for C27r from Kutz Canyon (table 4).

The duration of the Gallegos Canyon measured section was calculated by extrapolating the C29n and C28r sediment accumulation rates from De-Na-Zin and applying them to the measured C29r and C28r measured thickness respectively (table 5). The duration of the De-Na-Zin and Betonnie Tsosie Wash measured sections was calculated by extrapolating the C29n and C28r sediment accumulation rates from each location to the C29r and C28n measured section thickness respectively (table 5). The Kimbeto Wash measured section duration was calculated by extrapolating the average C29n sedimentation rate from De-Na-Zin and Betonnie Tsosie Wash to the C29r sediment thickness for the base of the section and extrapolating the C28r sediment accumulation rate from Kimbeto Wash to C28n sediment thickness (table 5). The duration of the Kutz Canyon measured section was done by extrapolating the C27r sediment accumulation rate down to the C28n sediment thickness and applying the C27r sedimentation rate to the total thickness of C27r sediments within the measured section (table 5). The duration of the Chico Springs measured section was calculated by extrapolating the C27r sediment accumulation rate from Kutz Canyon to the C28n and C27r sediment thickness (table 5). The Mesa de Cuba Measured section duration was calculated by extrapolating the average C29n sedimentation rate from De-Na-Zin and Betonnie Tsosie Wash to the Mesa de Cuba C29n thickness and by correlating the "lower black mudstone" to the same lithologic marker bed from Torreon West (Leslie et al., 2018b) (table 5).

$^{40}Ar/^{39}Ar$ Geochronology

Fine- to medium-grained sandstones were collected from De-Na-Zin, Betonnie Tsosie and Mesa de Cuba sections and prepared for $^{40}Ar/^{39}Ar$ detrital sanidine geochronology. The argon data are presented in Tables DR5-8 and table footnotes provide information of calculation methods for maximum deposition ages (MDA), correction factor data, flux monitor and decay constants. Recovery of sanidine evolved over the course of the project, however all samples were either gently crushed in a jaw crusher and ground in a disc grinder or hand crushed using a mortar and pestle. Samples were washed ultrasonically in dilute HCl until signs of calcite were no longer present, though most samples showed no evidence of calcite. Samples were further ultrasonically treated in distilled water and rinsed in acetone to expedite drying. Samples were then inspected for sanidine content under a petrographic microscope while immersed in wintergreen oil and based on this a grain size (typically between 45 and 120 mesh) was chosen to maximize sanidine recovery. K-feldspar was concentrated by heavy liquid floatation and from this concentrate we initially picked for sanidine based on optical clarity under a standard binocular microscope. This method was not fully effective at distinguishing sanidine from clear plutonic and/or metamorphic K-feldspar and we suggest that most detrital grain ages older than at least 500 Ma are likely not sanidine. To improve sanidine recovery for samples analyzed later in the study (i.e., Betonnie Tsosie section), K-feldspar concentrates were placed in a petri dish, covered in wintergreen oil and viewed under a polarizing binocular microscope with transmitted light. This allowed us to pick mostly sanidine by avoiding K-feldspars with microtextures that could not be easily observed under a standard binocular microscope.

A total of 13 detrital sanidine concentrates were irradiated in several packages at the USGS Triga reactor in Denver, CO, along with flux monitor standard Fish Canyon sanidine (FC-2). FC-2 was assigned an age of 28.201 Ma (Kuiper et al. 2008) and a total ^{40}K decay constant of

5.463e-10 /a was used (Min et al., 2000). Following irradiation, argon was extracted from single grains by either total fusion (SCLF) or low resolution (2-6 step) incremental heating with a CO_2 laser. Typical heating was 30 seconds followed by gas cleanup for 30-180 seconds. Argon isotopes were measured on ARGUS VI mass spectrometers with various Faraday resistor configurations (see details Tables DR5-8) for masses 40, 39, 38, and 37 whereas mass 36 was measured with a CDD ion counter. Typically masses 40 and 39 were determined using 1E13 Ohm resistors whereas masses 38 and 37 were measured using 1E12 Ohm resistors. Procedural blanks, air standards and calibration gas (enriched in radiogenic ^{40}Ar and ^{39}Ar) were measured numerous times during the course of data collection. These measurements were fit with a time-series analysis (typically averaged or fit with linear regression) and applied to the sample analysis to correct for blank, atmospheric argon and detector drift. All data are relative to flux monitor standard Fish Canyon sanidine (FC-2) with an age of 28.201 Ma (Kuiper et al., 2008) and use a ^{40}K total decay constant of 5.463×10^{-10} /a (Min et al., 2000). Since our primary goal was to find Paleocene grains to define maximum deposition ages, many analyses were truncated during the data collection when the calculated age was substantially older than 66 Ma, thus many of these older grains have overall lower precision due to shorter counting times in the mass spectrometer. Maximum deposition ages were calculated from the youngest mode of grain ages based on an inverse variance weighted mean (Taylor, 1982). In some cases, only one grain defines the youngest mode and in these cases the apparent age of the single grain is reported.

RESULTS

Magnetostratigraphy

Six hundred and ninety-one sample from 241 sampling horizons were analyzed during this study: 68 samples were analyzed from 25 sampling horizons from Kutz Canyon, 36 samples from 12 sampling horizons from Chico Springs, 73 samples from 24 sampling horizons from Gallegos Canyon, 146 samples from 50 sampling horizons from De-Na-Zin, 93 samples from 32 sampling horizons from Kimbeto Wash, 150 samples from 52 sampling horizons at Betonnie Tsosie Wash, and 124 samples from 46 sample horizons at Mesa de Cuba. Most samples were fully demagnetized by 150° to 400°C and their demagnetization trajectory trended towards the origin after few heating steps (fig. 5A-E). All specimens with reliable demagnetization trajectories and stable endpoints were characterized by line fits. This generated reliable paleomagnetic directions for 473 samples from 195 sampling horizons (fig. 6A; Table DR1): 47 samples (9.9 % of reliable samples) from 22 sampling horizons at Kutz Canyon, 48 samples (10.1% of reliable samples) from 18 sampling horizons at Gallegos Canyon, 17 samples (3.6% of reliable samples) from 8 sampling horizons at Chico Springs, 112 samples (23.7 % of reliable samples) from 43 sampling horizons at De-Na-Zin, 63 samples (13.3 % of reliable samples) from 25 sampling horizons at Kimbeto Wash, 102 samples (21.6 % of reliable samples) from 42 sampling horizons at Betonnie Tsosie, and 84 samples (27.6 % of reliable samples) from 37 sampling horizons at Mesa de Cuba. The remaining 217 samples (31.4% of total samples) had incoherent demagnetization trajectories and reliable directions could not be generated (fig. 5F).

Ninety-five of these sampling horizons (39.4% of total sampling horizons) had at least 3 samples with statistically significant directions that could be used to calculate site-mean directions with an α_{95} <35°: 10 from Kutz Canyon, 12 from Gallegos Canyon, 2 from Chico Springs, 26 from De-Na-Zin, 9 from Kimbeto, 24 from Betonnie Tsosie, and 13 from Mesa de Cuba (fig. 5B; Table DR2).

The site-mean directions for each section were calculated according to their polarity (fig. 5C) and also calculated at the formation level for each interpreted magnetic chron and for total reversed (chrons 29r, 28r, and 27r) and normal (chrons 29n and 28n) directions, generating mean Ojo Alamo Sandstone and lower Nacimiento Formation directions (fig. 5D). The site mean directions were then used to calculate VGP latitude and longitude for each magnetic chron and for all reversed and normal direction site means (table 2). The average Ojo Alamo Sandstone and lower Nacimiento Formation normal site-mean directions was oriented at 349.9°, 52.9° (n = 66, α_{95} = 3.9°) and the average reversed site-mean direction was oriented at 164.9°, -51.1° (n = 29, α_{95} = 5.1°). The reversal test of McFadden and McElhinny (1990) returned a positive, class A reversal test, indicating that it is not possible to reject the hypothesis that the two distributions share a common mean direction at with 95% confidence (i.e., passed reversals test). These directions overlap within uncertainty with the expected early Paleocene (65.5 Ma) direction of 343.0°, 49.7° recalculated from Torsvik et al. (2008) and the mean characteristic remanent direction of 342.1°, 49.6° (n = 20, α_{95} = 7.1°) for the Nacimiento Formation from Kodama (1997) (fig. 6D; table 2). The mean VGP latitude and longitude calculated from all normal polarity site means was 81.4 °N, 161.6 °E (N = 66, A_{95} = 5.8°) and for all reversed polarity site means was 76.9 °N, 152.7 °E (N = 29, A_{95} = 6.1), which is very similar to the early Paleocene (65.5 Ma) expected paleopole of 74.7 °N, 190.6 °E recalculated from Torsvik et al. (2008) (table 2).

Figure 2 shows the lithostratigraphy, local polarity stratigraphy, specimen and site-mean polarity, and specimen and site-mean VGP latitude for the Gallegos Canyon and De-Na-Zin measured sections. The reversal between local polarity zones A- and B+ is constrained to 3.0 m at Gallegos Canyon and 1.75 m at De-Na-Zin (fig. 2; table 3). The reversal between local polarity zones B+ and C- is constrained to 1.5 m at Gallegos Canyon and 0.7m at De-Na-Zin (fig. 2; table 3). The reversal between local polarity zones C- and D+ at De-Na-Zin is constrained to 3.0 m (fig. 2; table 3).

Figure 3 shows the lithostratigraphy, local polarity stratigraphy, specimen and site-mean polarity, and specimen and site-mean VGP latitude for the Kimbeto and Betonnie Tsosie Wash measured sections. The reversal between local polarity zones A- and B+ is constrained to 1.5 m at both Kimbeto and Betonnie Tsosie Washes (fig. 3, table 3). The reversal between local polarity zones B+ and C- is constrained to 1.5 m at Kimbeto Wash and 0.55 m at Betonnie Tsosie Wash (fig. 3, table 3). The reversal between local polarity zones C- and D+ is constrained to 3.0 m at Kimbeto Wash and 4.5 m at Betonnie Tsosie Wash.

Figure 4 shows the lithostratigraphy, local polarity stratigraphy, specimen and site-mean polarity, and specimen and site-mean VGP latitude for the Kutz Canyon, Chico Springs, and Mesa de Cuba measured sections. The reversal in the Chico Springs section is constrained to 3.0 m and is constrained in the Kutz Canyon section to 1.5 m (fig. 4; table 3). The reversal between local polarity zones A+ and B- at Mesa de Cuba is constrained to 1.5 m, the reversal between local polarity zones B- and C+ is constrained to 1.5 m, and the reversal between local polarity zones C+ and D- is constrained to 2.0 m (fig. 3; table 3). The reversal between local polarity zones C+ and D- is positioned at the base of a large channel complex presumed to represent an unconformity within the section; without the conformity, the reversal is constrained to 9.0 m due to being coarse-grained sandstones in this interval (fig. 4).

Magnetic Mineralogy

The Triaxial IRM Lowrie tests for all samples indicated mixed mineralogy with the majority of IRM held by grains with coercivities of less than 100 mT (fig. 6). The large remanence drop between 100-200 °C in the low coercivity fraction suggests titanohematite as the most common magnetic mineral in all samples, which is similar to what was found in previous work in the San Juan Basin and in contemporaneous Laramide basins (Butler and Lindsay, 1985; Force et al., 2001; Sprain et al., 2016) (fig. 6). The secondary magnetic mineralogy of samples P13NZ07 and P16BT19 is likely hematite and/or maghemite due to the relatively high proportion of remanence held in the > 1T and 100-300 mT coercivities, loss of remanence at 700 °C, and the red coloring (fig. 6A-B). For sample P13OJ1 (fig. 6C), the secondary magnetic mineralogy is possibly the iron sulfide mineral greigite becoming magnetite >400 °C due to a large drop in 0-300 mT coercivities between 200-350 °C and the presence of numerous sulfur bearing layers in this lithology (Roberts, 1995). In the remaining samples, remanence held from 100 – 300 mT drops starting at 200 °C and is demagnetized by 400 °C, indicating the presence of intermediate titanohematite (Sprain et al., 2016), and/or demagnetized between 550 to 600 °C, which indicates the presence of magnetite (Dunlap and Özdemir, 1997).

At Chico Springs, Betonnie Tsosie Wash, and Mesa de Cuba, local polarity zones B-, C- and, B- respectively are dominated by samples with erratic demagnetization behavior and we were only able to calculate good directions for a small subset of samples. We interpret these intervals to be reversed, with a large subset of samples recording an overprint direction (figs. 2-3). We analyzed four samples from Mesa de Cuba that span the predominantly overprinted section corresponding with the top of magnetozone A+, B-, and the bottom of C+ (fig. 6E-H). Two lines with a reliable normal demagnetization trajectory were produced from sample P14MC02 (fig. 6E), sample P14MC04 had an incoherent demagnetization trajectory (fig. 6F), a reversed great circle could be calculated from sample P14MC06 (fig. 6G), and a reliable normal site mean was calculated from sample P14MC12 (fig. 6H; Tables DR1-3). In all of these samples, the dominated magnetic carrier is titanohematite, which is frequently overprinted (Dunlop and Ozdemir, 1997; Sprain et al., 2016). In all samples, there is evidence that magnetite is a secondary magnetic mineral. Samples with a relatively high proportion of magnetite (i.e., P14MC02, P14MC06, P14MC12; fig. 6E, G-H) produced reliable magnetic directions while samples with relatively little magnetite (P14MC04, fig. 6F) produced incoherent directions. Thus, we hypothesize that while titanohematite is the most common magnetic mineral in these Betonnie Tsosie and Mesa de Cuba samples, magnetite is the characteristic remanent magnetization carrier, and that in the overprinted interval, samples with relatively small proportions of magnetite were either overprinted or had erratic demagnetization behavior.

^{40}Ar/^{39}Ar Geochronology

The detrital sanidine (DS) results are presented on age probability plots arranged in stratigraphic order and separated into their three measured sections (fig. 8). Also, we include the probability plot of sanidine from a minimally reworked volcanic ash (sample SJ-Ash-2) from the Da-Na-Zin section that is published in Cather et al. (2019) for comparison with the DS spectra. Sample A1070606 from Mesa de Cuba overall has individual crystal ages range between Paleocene and Precambrian with many grains being late Cretaceous in age. As mentioned, grains older than ~500 Ma are likely non-sanidine whereas grains younger than 300 Ma are likely sanidine. Age spectrum analyses of single grains (Tables DR5-7) are generally flat and thus yield plateau ages equal to total gas ages, supporting the validity of the total fusion ages.

Two samples (SJ-SS5 and CM-SS4) from the Ojo Alamo Sandstone (one from De-Na-Zin and one from Mesa de Cuba) yield mostly Upper Cretaceous or older grains (fig. 8). A single grain from CM-SS4 is 65.69±0.09 Ma and represents the only Paleocene DS grain recovered from Ojo Alamo samples. For the Nacimiento Formation, a minor component of Paleocene grains were recovered from many of the samples and provide useful maximum deposition ages (MDA) (fig. 8). Generally, the mode of youngest Paleocene grains consists of less than five grains, however the Paleocene mode from A16-BTW-MH2 has 13 grains and CM-SS2 has seven. Three of the five samples from Betonnie Tsosie did not yield Paleocene grains, but rather have a substantial component around 68 Ma, as well as many older late Upper Cretaceous DS grains. In a single instance, a DS grain appears anomalously young based on other information that will be discussed below. This grain comes from sample A16-BTW-MH5 and yields an apparent age of 64.48±0.16 Ma and although imprecise it is statistically younger than the preferred MDA of 65.17±0.06 Ma defined by three grains (fig. 8, Appendix 5).

Sample A1070606 is a recollection of what appears to be significantly reworked ash from Mesa de Cuba. Fassett et al. (2010) first reported an age of 64.5±0.2 (1σ) Ma for this unit and new analysis yields a more precise age of 64.61±0.06 Ma (Fig. 7). CM-Ash-1 was collected at the same stratigraphic level as A1070606, but about 1 km to the west and analysis did not yield any Paleocene grains perhaps emphasizing the reworked nature of the unit. These “ash” samples have a significant component of microcline and contrasts for SJ-SS-2 ash that is dominated by sanidine with very minor inherited microcline.

Relationship of Polarity Stratigraphy to GPTS

Based on lithostratigraphic correlations between the sections, the similarity of the patterns and stratigraphic position of reversal boundaries, and the ash and detrital dates, we correlated the A-, B+, C- local polarity zones from Gallegos Canyon, De-Na-Zin, Kimbeto Wash, and Betonnie Tsosie Wash with C29r-28r and local polarity zone D+ from De-Na-Zin, Kimbeto Wash, and Betonnie Tsosie Wash with C28n. These correlations are the same as the interpretations from Butler and Lindsay (1985) (figs. 2-3). Using the polarity interpretations from Kutz Canyon of Leslie et al. (2018b) and Taylor and Butler (1980), which correlates to the top of our section, we correlated the local polarity zones A+ and B- from Kutz Canyon and Chico Springs to C28n-27r (fig. 4).

No polarity stratigraphy from Mesa de Cuba has previously been published. Our section contains A+, B-, C+, and D- magnetozones. Reworked ash sample A1070606 from an ash layer at 65 m in the section yields an $^{40}Ar/^{39}Ar$ age of 64.61±0.06 Ma. This sample is within magnetozone C+, which indicates correlation with C28n (fig. 3). Sample CM-SS3 is from ~3 m in the section and within magnetozone A+. The detrital sanidine MDA is 65.67±0.08 Ma, and because there is a magnetically reversed interval between A1070606 and CM-SS3 we can confirm that the MDA of this sample places this interval within C29n. Thus, we correlate magnetozones A+, B-, C+, and D- at Mesa de Cuba to C29n-27r (fig. 3).

Sediment Accumulation Rates and Measured Section Duration

Sedimentation accumulation rates we calculated for C29n from De-Na-Zin (43.3 +6.5/-5.4 m/Myr) and Betonnie Tsosie Wash (41.6 +7.9/-6.5 m/Myr) were nearly identical and overlap within uncertainty (table 4). The C29n sediment accumulation rates from Gallegos Canyon (31.6 +6.8/-5.6 m/Myr) and Kimbeto Wash (27.7 +7.5/-6.9 m/Myr) overlap within uncertainty of each other and were approximately half the average sedimentation rate from De-Na-Zin and Betonnie Tsosie (fig. 2; table 4). The Gallegos Canyon section has an interval of significant channelization ~27 m above the Ojo Alamo Sandstone-Nacimiento contact. Additionally, the base of C29n at Kimbeto Wash occurs in a channelized sandstone complex (fig. 2). Based on the sedimentology and sediment accumulation rates, we interpret unconformities to occur in Gallegos Canyon at the channelized interval (fig. 2) and in the Kimbeto Wash section at the channelized sandstone complex (fig. 3). Applying the C29n sedimentation rate of 43.3 m/Myr (+6.5/-5.4 m/Myr) from De-Na-Zin to the Gallegos Canyon section, we estimate that the duration of C29n sedimentation at Gallegos Canyon is 0.53 Myr (+0.14/-0.12 Myr), indicating an unconformity duration of 0.20 Myr. We estimate that the unconformity occurs from 65.39 – 65.19 Ma (fig. 8, table 5). When the C29n sedimentation rate from Betonnie Tsosie Wash of 41.6 m/Myr (+7.9/-6.5 m/Myr) is applied to the Kimbeto Wash section, the duration of C29n sedimentation is estimated at 0.51 Myr (+0.14/-0.11 Myr), indicating an estimated unconformity duration of 0.22 Myr between 65.69 – 65.47 Ma (fig. 8; table 5).

Sedimentation accumulation rates we calculated for C28r from De-Na-Zin (92.3 +16.9/-13.9 m/Myr), Kimbeto Wash (101.0 +22.2/-18.3 m/Myr), Betonnie Tsosie Wash (138.8 +14.8/-21.6 m/Myr), and Mesa de Cuba (92.8 +15.6/-12.8 m/Myr) were similar to each other and roughly double the sedimentation rates from C29n (table 4). Additionally, sedimentation rates are highest in Betonnie Tsosie Wash near the basin center where thick channel sandstone are present. The only measured section which constrains the lower and upper reversals of C28n is at Mesa de Cuba (fig. 3). The calculated C28n mean sediment accumulation rate using the chron thickness from Mesa de Cuba was 39.6 m/Myr (+12.8/-10.5 m/Myr), which is significantly lower than the C28r sedimentation rates from the same section. The basal contact between magnetozone C+ and D- at Mesa de Cuba occurs at the base of a large channel sandstone complex that has an erosive basal contact (fig. 3). Based on the erosive nature of the basal contact of the sandstone channel complex and the very low sediment accumulation rates, we infer the presence of an unconformity within C28n at Mesa de Cuba (table 4). We placed the unconformity at the base of a large channel complex, which erosively overlies the last normal polarity points in C28n (fig. 3). When the C28r sedimentation rate from Mesa de Cuba is applied to the C28n section thickness, the C28n duration at Mesa de Cuba is estimated to be 0.420 Myr (+0.07/-0.06 Myr) (table 5).

The C27r sedimentation accumulation rate we calculated from Kutz Canyon is 121.8 m/Myr (+24.8/-18.8 m/Myr), similar to the estimated C27r sediment accumulation rates from Taylor (1977) and nearly identical to those calculated by Leslie et al. (2018b) for C27n from the same location (table 4). Since the upper most sample in the Kutz Canyon measured section presented in this paper (fig. 3) is the lower most sample in the Kutz Canyon section from Leslie et al. (2018b), we could estimate a total thickness for C27r.

Based on its lithology and polarity, the upper 3.0 m of the Mesa de Cuba measured section can be correlated with the "lower black mudstone" from Leslie et al. (2018b). Using the age estimate of 62.82 Ma for the "lower black mudstone" from Torreon West in Leslie et al. (2018b) for the top of the Mesa de Cuba section and the C27r sediment accumulation rate from Kutz Canyon, the duration of C27r at Mesa de Cuba is estimated to be 0.48 Myr (+0.09/-0.08 Myr) and the base of the C27r portion of the section is estimated to be 63.30 Ma (fig. 3, 8; table 5). Thus, we estimate the total unconformity duration between C28n and C27r at Mesa de Cuba to be 0.95 Myr from 64.25 – 63.30 Ma (fig. 8; table 5).

The Gallegos Canyon section spans 66.05 Ma (+0.11/-0.08 Myr) to 64.71 Ma (+0.07/-0.08 Myr) for a total section duration of 1.35 Myr (+0.19/-0.21 Myr) (fig. 8; table 5). The De-Na-Zin section spans 66.15 Ma (+0.12/-0.15 Myr) to 64.26 Ma (+0.18/-0.20 Myr) for a total section duration of 1.89 Myr (+0.32/-0.30 Myr) (fig. 8, table 5). The Betonnie Tsosie Wash section spans 65.83 Ma (+0.10/-0.12 Myr) to 64.43 Ma (+0.15/-0.16 Myr) for a total section duration of 1.39 Myr (+0.26/-0.24 Myr) (fig. 8; table 5). The duration of the Kimbeto Wash section is 65.82 Ma (+0.06/-0.09 Myr) to 64.45 Ma (+0.15/-0.18 Myr) for a total section duration of 1.37 Myr (+0.22/-0.24 Myr) (fig. 8; table 5). The Kutz Canyon section spans 63.82 Ma (+0.20/-0.20 Myr) to 62.76 Ma (+0.26/-0.28) for a total section duration of 1.06 Myr (+0.48/-0.46 Myr) (fig. 8; table 5). The Chico Springs section spans 63.51 Ma (+0.15/-0.15) to 63.03 Ma (+0.22/-0.23 Myr) for a total section duration of 0.48 Myr (+0.39/-0.37 Myr) (fig. 8; table 5). The Mesa de Cuba section spans 65.552 Ma (+0.108/-0.082 Myr) to 62.820 Ma (+0.175/-0.143 Myr) for a total section duration of 2.732 Myr (+0.251/-0.257 Myr) (fig. 8; table 5).

DISCUSSION

San Juan Basin Evolution

Age and depositional model of the Ojo Alamo Sandstone

The precise age of the Ojo Alamo Sandstone has been contentious, with disagreements about the duration of the underlying unconformity with the Naashoibito Member and how far into the lower Paleocene the Ojo Alamo Sandstone extends (Sullivan and Lucas, 2003; Sullivan et al., 2005; Williamson et al., 2008; for Fassett, 2009). Previous palynostratigraphy placed the Ojo Alamo Sandstone in the lower Paleocene palynostratigraphic zones P1 or P2 (Anderson, 1959; Williamson et al., 2008) and analyses of the megaflora also suggests an early Paleocene age (Flynn and Peppe, in press). The Ojo Alamo Sandstone is an average of 12 m thick and varies from 5 – 17 m in De-Na-Zin. Using the average thickness for the Ojo Alamo and the C29n sediment accumulation rates of the overlying Nacimiento Formation, we estimate that the base of the Ojo Alamo is 66.15 Ma (+0.012/-0.15 Myr), which is approximately 150 Kyr before the K/Pg boundary (Renne et al., 2013). There are two important caveats to this age estimate: first there are dramatic sedimentological differences between the Ojo Alamo and the Nacimiento

Formation, and sediment accumulation rates were likely much higher during deposition of the Ojo Alamo Sandstone, which is a massive multi-stored channel complex (for example, Baltz et al., 1966; Cather, 2004; Chapin and Cather, 1983; Flynn and Peppe, in press), than the Nacimiento Formation, which is comprised of paleosols, floodplain, overbank, back swamp, and ponded deposits, and channels of varying size and dimensions (for example Cather et al., in press; Davis et al., 2006; Williamson, 1996). Second, there is an erosive basal contact between the Ojo Alamo Sandstone and Naashoibito Member, indicating that there is an unconformity between the Paleocene Ojo Alamo Sandstone and the Cretaceous Naashoibito. Thus, this method almost certainly overestimates the duration of the Ojo Alamo Sandstone and is a maximum depositional age. The onset of deposition of the Ojo Alamo Sandstone probably post-dates the K/Pg boundary and the formation likely samples much of the lower Paleocene C29r.

When compared across the basin, the polarity stratigraphy, sediment accumulation rates, and a detrital sanidine date from the Ojo Alamo Sandstone all indicate that the Ojo Alamo-Nacimiento formational contact is time transgressive from northwest to southeast (fig. 2-4). The Ojo Alamo Sandstone-Nacimiento Formation contact is in C29r in Gallegos Canyon, De-Na-Zin, and Betonnie Tsosie Wash, but in C29n at Mesa de Cuba. The C29n polarity interpretation for Mesa de Cuba is supported by a detrital sanidine $^{40}Ar/^{39}Ar$ date of 65.68 Ma ± 0.09 Myr just below the Ojo Alamo-Nacimiento formational contact near Mesa de Cuba (fig. 8). Based on these polarity interpretations and local sediment accumulation rates for C29n of the Nacimiento Formation, we constrain the age of the Ojo Alamo Sandstone-Nacimiento Formation contact at Gallegos Canyon to 66.02 Ma (+0.05/-0.04 Myr), 65.87 Ma (+0.03/-0.02 Myr) at De-Na-Zin, 65.83 Ma (+0.03/-0.02 Myr) at Betonnie Tsosie Wash, and 65.63 Ma (+0.12/-0.11 Myr) at Mesa de Cuba (fig. 2-4). Using these age constraints for the formational contact, we interpret deposition of the Ojo Alamo Sandstone to have occurred during the first ~350 Kyr of the lower Paleocene in the northern parts of the basin and within the first ~500 Kyr of the lower Paleocene in the southern parts of the basin.

Based on the time transgressive nature of the contact and the sedimentology of the unit, we interpret the Ojo Alamo Sandstone to represent the progradational proximal deposits of a distributed fluvial system (DFS) (Weissmann et al., 2013; Hobbs, 2016) and the basal Nacimiento Formation to represent the distal deposits of a later DFS. Thus, we suggest that the time transgressive nature of the Ojo Alamo Sandstone-Nacimiento Formation contact is the result of basin infilling in the early Paleocene via the progradation of a large DFS.

Age and depositional model of the lower Nacimiento Formation

The calculated sediment accumulation rates for C29n were relatively low suggesting limited available accommodation space in the SJB prior to and during C29n (table 4). Interestingly, sediment accumulation rates roughly double in C28r and are not equal across the basin with sedimentation rates highest in Betonnie Tsosie Wash and lowest in De-Na-Zin and Mesa de Cuba on the basin margin suggesting creation of additional accommodation near the C29n-C28r boundary and remain >90 m/Myr for at least the succeeding ~2.75 Myr (e.g., through chron 27n; table 4; this study and Leslie et al., 2018b). We interpret this increase in sedimentation rates to have been caused by a significant increase in accommodation created by increased subsidence rates in C28r through C27n.

Cather (2004) hypothesized a three-phase subsidence model for the Upper Cretaceous – Eocene deposits of the San Juan Basin. In particular, Cather (2004) argued for a phase of subsidence from ~74-67 Ma that allowed for the deposition of the Ojo Alamo Sandstone and

Nacimiento Formations. Based on our age constraints for the Ojo Alamo Sandstone and Nacimiento Formation, we modify Cather's (2004) subsidence model. We propose that the initial onset of subsidence and creation of accommodation space in the Maastrichtian allowed the deposition of the Maastrichtian Naashoibito Member of the Kirtland/Fruitland Formations, the Ojo Alamo Sandstone, and the lower (C29n) portion of the Nacimiento Formation. Later, in C28r, a second pulse of increased subsidence created accommodation space allowing the deposition of the upper portion of the Nacimiento Formation before subsidence slowed in the middle Paleocene, ultimately creating the unconformity between the Nacimiento Formation and the overlying San Jose Formation. The third phase of subsidence then occurred at some point in the late Paleocene to early Eocene, allowing the deposition of the Eocene San Jose Formation. Determining the age of the third phase of subsidence will require precise dating of both the uppermost Escavada Member of the Nacimiento Formation and the San Jose Formation, which should be the focus of future work in the San Juan Basin.

Using this refined model of basin subsidence, we can make interpretations about the drivers of deposition of the Nacimiento Formation. The lower Nacimiento Formation, correlated with C29n, is dominated by poorly developed paleosols and pond deposits (Davis et al., 2016). Channels in this interval tend to be small and/or isolated, with an overall increase in channelization towards the end of C29n (fig. 2-4). In C28r and C28n, channelization becomes more common and paleosols become better developed (fig. 2-4). The approximate doubling of sedimentation rates in C28r agrees with the basin subsidence model by Cather et al. (2019) which found an increase in basin subsidence during the early Torrejonian and the development of the large Tsosie paleoriver during this time interval. The high degree of channelization during C28r, especially in the Kimbeto and Betonnie Tsosie Wash sections, likely reflect the emplacement of the Tsosie paleoriver (Cather et al., 2019). Towards the top of C28n in Kutz Canyon, large sheet sands become common (fig. 4). In C27r, grain size is the greatest with a high amount of sheet sands near the basin center at Kutz Canyon, while smaller sheet sands and paleosols are present at the basin margin at Mesa de Cuba (fig. 4). The presence of large-scale sheet sands in C27r suggest an accommodation minimum resulting in unconfined flow when the sediment transport capacity of the channel was exceeded, which is consistent with the conclusions of Leslie et al. (2018b) for the upper Nacimiento Formation. We hypothesize that the Nacimiento Formation represents a progradational DFS, overlying the previous Maastrichtian-earliest Paleocene DFS capped by the Ojo Alamo Sandstone, with the C29n deposits representing the distal portion of the DFS and the C27r deposits representing the more proximal part (e.g., Trendell et al., 2013; Weissmann et al., 2013). However, the sedimentological and mineralogical data needed to test this hypothesis fully is beyond the scope of this paper and further research is needed.

Age Constraints on San Juan Basin Mammalian Biozones

We constrained the age of Puercan and earliest Torrejonian vertebrate fossil horizons of the Nacimiento Formation within our measured sections (table 1) using our estimated sediment accumulation rates (table 4). Using our magnetostratigraphic correlations among sections and the age constraints for each fossil locality, we were able to calculate the ages and durations of the Nacimiento Formation mammalian biostratigraphic zones (Pc1, Pc2, Tj1-Tj5) (fig. 9, table 1). These results indicate that strata in which the Pc1 and Pc2 faunas have been found are restricted to C29n, Tj1 faunas occur only in C28n, and the Tj2 and Tj3 faunas in C27r (fig. 8, table 1). Combining our results with the work of Leslie et al. (2018b), which determined that Tj4 and Tj5 faunas occurred within C27r and the Tj6 faunas occurred within C27n, corroborates previous interpretations of the early Paleocene NALMA biochronologic interval zones for the SJB (e.g., Lofgren et al., 2004). Importantly it also provides more precise age constraints for the first and last occurrences and durations of the Puercan and Torrejonian equivalent biozones in the SJB. This has global implications for understanding mammal evolution after the end-Cretaceous mass extinction.

Because both Pc1 and Pc2 faunas (i.e., Pu2 and Pu3) in the SJB occur within C29n, the duration of each biozone was previously uncertain (Williamson and Lucas, 1992; Williamson, 1996). We constrained Pc1 fossil horizons from De-Na-Zin, Kimbeto Wash, and Betonnie Tsosie Wash to 65.68 – 65.34 Ma (+0.04/-0.01 Myr) for a total duration of 340 ± 50 Kyr (fig. 9, table 1). This demonstrates that, at maximum, the Pc1 mammals occurred within 380 kyr of the K-Pg boundary. We were also able to constrain the Pc2 fossil horizons from Gallegos Canyon and De-Na-Zin to 65.27 – 65.03 Ma (+0.03/-0.01 myr) for a total duration of 240 ± 40 Kyr (fig. 9, table 1). The only section where Pc1 and Pc2 are found in superposition is in De-Na-Zin (fig. 9, table 1). The duration in De-Na-Zin between strata with Pc1 and Pc2 faunas was 360 ± 70 Kyr (table 1). However, the Pc1 fossil site in De-Na-Zin is the oldest horizon in the basin and if the full duration of Pc1 fossil-bearing interval is used, the gap between Pc1 and Pc2 fossil horizons was 70 ± 90 Kyr (fig. 9, table 1).

We were able to constrain the Tj1 fossil-bearing interval in the SJB to C28n from 64.66 – 63.76 Ma (+0.07/-0.09 Myr) for a total duration of 900 Kyr (+70/-90 Kyr) (fig. 9, table 1). Interestingly, fossil horizon 5 (locality AMNH 230; Simpson, 1969) at Mesa de Cuba (table 1), contains diagnostic Tj1 mammals, but unfortunately the stratigraphic position of the locality is uncertain. Using measurements and descriptions from Simpson (1959) for the locality (AMNH 230), we estimate that it most likely occurs between 40 and 50 m in our Mesa de Cuba section, which would suggest an age of 64.80-6474 Ma (+0.04/-0.02 Myr) making the base of Tj1considerably older. However, because we were unable to relocate the site, it was not used to determine either SJB mammal biozone or biochronologic interval zone boundaries (fig. 9, table 1). Even without the Simpson (1959) site, these results indicate that the base of the Tj1 biozone is considerably older than previously suggested (e.g., Williamson, 1996; Lofgren et al., 2004) and that the 'barren interval' is much shorter (Williamson, 1996). Using our revised chronology, the interval between Pc2 and Tj1 faunas (i.e., the "barren interval") is 380 kyr (+120/-110 kyr) (fig. 9, table 1).

Combining our magnetostratigraphy with that of Leslie et al. (2018b) allowed us to determine that SJB biozones Tj2-5, which are equivalent to the To2 biochron of Lofgren et al. (2004), occurred within C27r from 63.48 – 62.59 Ma (+0.03/-0.04 Myr) for a total duration of 890 kyr (+30/-40 kyr) (fig. 9, table 1). In Kutz Canyon, To1 and To2 faunas occur in superposition, and this is the type area for the NALMA zone interval change (Lofgren et al., 2004). Using the uppermost Tj1 horizon (vertebrate horizon 8; table 1) and the lowermost Tj2 horizon (vertebrate horizon 9; table 1), the transition between Tj1 and Tj2 faunas occurred over 280 Kyr (+80/-90 Kyr) (table 1, fig. 9).

Regional NALMA interval zone chronology comparison

The revised age model for SJB faunal zones has important implications for regional patterns of first and last occurrences of the biochronologic zones of Lofgren et al. (2004) across North America. It should be noted, though, that these biochrons are based on the first occurrences of consecutive taxa (interval zones) and that by definition each zone lasts until the first occurrence of the next younger index taxon. For this reason, the zones extend through unfossiliferous intervals in the SJB, which adds uncertainty about the placement of upper and lower boundaries. The magnitude of this uncertainty is dependent on the duration of the unfossiliferous interval (fig. 9). We proceed by describing where the placement of zone boundaries lie chronostratigraphically based solely on the occurrences of fossils.

Our results indicate that biochrons Pu2 and Pu3 occur within C29n in the San Juan Basin, which is consistent with interpretations from the Williston Basin (LeCain et al., 2014; Sprain et al., 2015, 2018), Crazy Mountain Basin (Buckley, 2018), the Wasatch Plateau (Tomida and Butler, 1980) and the Denver Basin (Eberle, 2003; Hicks et al., 2003) (fig. 10). Previous work from the Williston Basin suggests that Pu2 first occurred in upper C29r (Peppe et al., 2009) in the Northern Great Plains, which indicates that the first occurrence of Pu2 taxa was diachronous across North America (fig. 10), suggesting differential regional responses to the K-Pg extinction, and possible time transgressive immigration of mammalian taxa. However, it is difficult to test this hypothesis because no *in situ* vertebrate remains have been found in strata correlative to C29r in the SJB. The Ojo Alamo Sandstone, which has yet to yield any mammal fossils, comprises most of the C29r strata in the basin and the lowermost occurrence of Pu2 occurs within 2 m of the C29r-C29n boundary (figs. 2, 9, 10). Given the dramatic change in depositional environments between the Ojo Alamo Sandstone and the Nacimiento Formation, the lack of mammals in C29r in the San Juan Basin is probably the result of taphonomic constraints. Thus, it is possible that taphonomy could explain the restriction of Pu2 taxa to C29n in the SJB, and that the first appearance of Pu2 taxa may not have been regionally diachronous (fig. 10).

Our results indicate that in the SJB the duration between Pu2 and Pu3 fossil localities was very short. Furthermore, age constraints for Pu1 localities from other basins (e.g., Eberle, 2003; Hicks et al., 2003; Peppe et al., 2009; Sprain et al., 2015, 2018) combined with either the maximum age of Pu2 fossil sites (i.e., in C29r, Peppe et al., 2009), or the age of Pu2 sites from the SJB (65.68 Ma), also imply a rapid turnover between Pu1 and Pu2 faunas (fig. 9). Both the Pu1-Pu2 and the Pu2-Pu3 turnovers are characterized by the extinction of important zone taxa (e.g., Lofgren et al., 2004). The short durations between Pu1-Pu2 and Pu2-Pu3 fossil sites suggest that the Puercan is characterized by the relatively rapid turnover of earliest Paleocene "disaster taxa" to more diverse recovery faunas (Smith et al., 2018).

The Puercan-Torrejonian boundary has been interpreted to have been nearly synchronous across North America, occurring in either late C28r or early C28n (Lofgren et al., 2004). However, To1 mammals occur in upper C29n in the Williston Basin of North Dakota and Montana (Peppe et al., 2009; Sprain et al., 2018) and the Crazy Mountain Basin of Montana (Buckley, 2018), in C28r from the Wasatch Plateau of Utah (Tomida and Butler, 1980), and from the base of C28n in the San Juan Basin (this study) (fig. 10). This suggests that the Puercan-Torrejonian boundary may be diachronous across North America, with the boundary being older in the north and younger in the south (fig. 10). Interestingly, in the SJB, the boundary between Pu3 and To1 faunas coincides with a major turnover in the mammalian fauna hypothesized to be caused by the immigration of northern taxa into the SJB from further north (Williamson, 1996) consistent with our finding of continent-wide diachronicity.

The To1, To2, and To3 faunas are constrained to C28r, C27r, and C27n in the SJB, and as documented here, and by Leslie et al. (2018b), the turnover between faunas in the SJB is rapid. However, much like in the Puercan, it is difficult to determine if the patterns of faunal turnover documented in the SJB during the Torrejonian are representative of local or regional phenomena. This is because the SJB is the only basin in which faunas representing the entire Torrejonian occur in superposition (fig. 10), and even though there are collections of early and late Torrejonian mammals from outside the SJB (Butler et al., 1987; Leslie et al., 2018a;

Buckley, 2018), these faunas typically occur in isolation and are difficult to correlate precisely to the SJB record. Furthermore, in some cases, fauns have been recognized as being Torrejonian based on the occurrence of typical Torrejonian taxa, but not the diagnostic index species for the biochrons (for example, Hunter and Hartman, 2003). Thus, it is possible that these apparently older Torrejonian faunas may not be Torrejonian, and instead document the transition between the Puercan and Torrejonian. Nonetheless, our data combined with previously published work suggests that the timing of the Puercan-Torrejonian is unlikely to be time equivalent across North America and should be the focus of future work. Finally, give the occurrence of almost the entirety of the Puercan and Torrejonian in superposition at multiple sites, our work highlights the importance of the SJB for understanding early Paleocene mammalian evolution following the K-Pg mass extinction.

CONCLUSIONS

We correlate the lower Paleocene Ojo Alamo Sandstone and lower Nacimiento Formation to magnetic chrons C29r-C27r of the GTPS, based on seven measured sections across the SJB. This includes the first magnetostratigraphy for the type section of the Nacimiento Formation at Mesa de Cuba. We identified titanohematite as the most common magnetic mineral, but infer that (titano)magnetite, hematite, and possibly greigite are the characteristic remanence carriers. Our results indicate relatively low sediment accumulation rates in C29r and C29n and a roughly doubling of sedimentation rates in C28r, which remained consistently high through C27r and were similar to sedimentation rates reported by Leslie and others (2018a) for C27n. We amend the SJB basin evolution hypothesis from Cather (2004), and instead hypothesize that the onset of the middle phase of relatively slow subsidence started in the Maastrichtian. This phase allowed for deposition of the Naashoibito Member, Ojo Alamo

Sandstone, and the C29n portion of the Nacimiento Formation. This was followed by a pulse of high subsidence and likely development of the Tsosie paleo-river starting in C28r (Cather and others, 2019) allowing for the deposition of the remainder of the Nacimiento Formation. We find that the contact between the Ojo Alamo Sandstone and Nacimiento Formation is time transgressive, with the contact occurring in C29r in the northwest part of the basin (Gallegos Canyon, De-Na-Zin, Kimbeto Wash, and Betonnie Tsosie Wash) and in C29n in the southeast part of the basin (Mesa de Cuba). This time transgressive nature of the Ojo Alamo Sandstone indicates progradation from northwest to southeast during the early Paleocene. These results are consistent with the interpretation that the Ojo Alamo Sandstone and the Nacimiento Formation represent the proximal and distal deposits of two different distributive fluvial systems, respectively.

Our revised age model constrains the intervals in which Pu2 faunas occur in the SJB to 65.68 – 65.34 Ma (+0.04/-0.01 Myr), Pu3 faunas to 65.27 – 65.03 Ma (+0.03/-0.01 Myr), To1 faunas to 64.66 – 63.76 Ma (+0.07/-0.12 Myr), and the To2 faunas to 63.48 – 62.59 Ma (+0.03/-0.04 Myr). Our results indicate that Pu2 and Pu3 faunas are separated by ~70 Kyr and that Pu3 and To1 faunas in the SJB are separated by ~370 Kyr (+40 Kyr/-30Kyr). Our revised age model for the SJB suggests that the first appearance of To1 mammals was diachronous across North America, with the To1 mammals first appearing in the north (Montana and North Dakota) during C29n, then the middle latitudes (Utah) in C28r, and lastly in southern North America (New Mexico) in C28n. These findings have broad implications for understanding the tempo of mammal evolution after the end-Cretaceous extinction and suggest that a complex interplay of *in situ* rapid diversification, immigration, climatic changes, and regional tectonics produced rapid turnover in some of the first, and best-known, communities dominated by placental mammals after the dinosaur extinction.

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FIGURE CAPTIONS

Fig. 1. Geologic map of the San Juan Basin, New Mexico showing Upper Cretaceous through Lower Eocene strata and the locations of the 7 measured sections use in this study — (1) Kutz Canyon, (2) Gallegos Canyon, (3) Chico Springs, (4) De-Na-Zin Wilderness Area, (5) Kimbeto Wash, (6) Betonnie Tsosie Wash, and (7) Mesa de Cuba — indicated by white squares (modified from Williamson et al., 2008).

Fig. 2. Measured sections from Gallegos Canyon and De-Na-Zin showing major lithologic units, vertebrate fossil horizons (described in table 1), VGP latitude, and interpreted polarity zonation. The base of local polarity zone C- was used as a datum. The UTM coordinates (NAD27 datum) of the section base and top are shown below section names.

Fig. 3. Measured sections from Kimbeto and Betonnie Tsosie Washes showing major lithologic units, vertebrate fossil horizons (described in table 1), VGP latitude, and interpreted polarity zonation. The base of polarity zone C- was used as a datum. The UTM coordinates (NAD27 datum) of the section base and top are shown below section names.

Fig. 4. Measured sections from Kutz Canyon, Chico Springs, and Mesa de Cuba showing major lithologic units, vertebrate fossil horizons (described in table 1), VGP latitude, and interpreted polarity zonation. The base of local polarity zone B- at Kutz Canyon, B- at Chico Springs, and

D- at Mesa de Cuba was used as a datum. The UTM coordinates (NAD27 datum) of the section base and top are shown below section names.

Fig. 5. Representative orthogonal end vector demagnetization and equal area diagrams for each subset of data. (A-E) Demagnetization trajectories of reversed (A, C, E) and normal (B, D) polarity samples from C29r – C27r that allowed line-fitting to a determine characteristic direction. (F) Representative sample where line-fitting was not possible due to the erratic nature of the data and was not used in any interpretations.

Fig. 6. (A) Equal-area plot of all line-fitted characteristic magnetization direction obtained (see Table DR1 1 for full list). (B) Equal area plot of all site-mean directions calculated from this study (see Table DR2 for full list). (C) Equal area plot of all normal and reversed site-mean directions averaged by sections — KC: Kutz Canyon, DNZ: De-Na-Zin, KW: Kimbeto Wash, BT: Betonnie Tsosie Wash, and MDC: Mesa de Cuba. The ellipse surrounding each mean direction represents the 95% confidence cone (see table 2 for details) (Fisher, 1953). (D) The site-mean average for each magnetic chron (C29r-C27r) and total Ojo Alamo Sandstone and lower Nacimiento Formation mean normal and reversed directions. The mean Nacimiento formation direction reported by Kodama (1997) is also shown. The ellipse surrounding each mean direction represents the 95% confidence cone (see table 2 for details) (Fisher, 1953). The modern dipole, the expected early Paleocene direction recalculated from Torsvik et al. (2008), and the antipode of the early Paleocene expected direction are shown in each equal-area plot.

Fig. 7. Thermal demagnetization curves of orthogonal IRM imparted along the X, Y, and Z axes for 8 samples following the approach of Lowrie (1990). All samples had mixed magnetic mineralogy with titanohematite as the dominant magnetic carrier.

Fig. 8. $^{40}Ar/^{39}Ar$ sanidine probability distribution diagrams. Apparent ages between 60 and 80 Ma are shown and solid symbols delineate dates used to determine maximum deposition ages. The data are arranged in stratigraphic order and divided into the 3 dated stratigraphic sections. DNZ is the De-Na-Zin section, BT represent the Betonnie Tsosie Wash section and MDC is the Mesa de Cuba section. Figures highlighted in yellow are Nacimiento Formation whereas pink are from the Ojo Alamo Sandstone. Errors are reported at 1σ.

Fig. 9. Chronostratigraphy of the Ojo Alamo Sandstone and Nacimiento Formation showing the age, calculated duration, and associated NALMA intervals for the sections in this study (lower portion of Kutz Canyon, Gallegos Canyon, Chico Springs De-Na-Zin, Kimbeto Wash, Betonnie Tsosie Wash, and Mesa de Cuba) and sections from Leslie and others (2018a) (upper portion of Kutz Canyon, Escavada Wash, Torreon West, and Torreon East). GTPS is from Ogg (2012). The estimated duration of unconformities is indicated by dark grey boxes. Fossil vertebrate horizons described in table 1 are shown (1-14 this study, 15-23 Leslie et al., 2018b). Biozones following the biostratigrpahic zonation of Williamson (1996) and duration of SJB fossil horizons within each NALMA biochron are shown. The “lower black mudstone” lithology from Leslie and others (2018b) is indicated beside the sections where it is present.

Fig. 10. Regional comparison of NALMA interval zones across western North America: Big Bend, TX (Leslie et al., 2018a), San Juan Basin, NM (this study; Leslie et al. 2018b), Denver Basin, CO (Eberle, 2003; Hicks et al., 2003; Dahlberg et al., 2016), Wasatch Plateau, UT (Tomida and Butler, 1980), Bighorn and Clark's Fork Basin, WY and MT (Butler et al., 1987), Crazy Mountain Basin, MT (Buckley, 2018), Williston Basin, MT (Sprain et al., 2018), and Williston and Powder River Basins, ND (Peppe et al., 2009). NALMA zones from Lofgren et al. (2004) are indicated.